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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

REPORT SECURITY CLASSIFICATION (U)		1b RESTRICTIVE MARKINGS NA	
SECURITY CLASSIFICATION AUTHORITY NA		3 DISTRIBUTION / AVAILABILITY OF REPORT Distribution Unlimited	
DECLASSIFICATION / DOWNGRADING SCHEDULE NA		5 MONITORING ORGANIZATION REPORT NUMBER(S) NA	
PERFORMING ORGANIZATION REPORT NUMBER(S) NA		7a NAME OF MONITORING ORGANIZATION Office of Naval Research	
NAME OF PERFORMING ORGANIZATION University of Pennsylvania		7b ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217-5000	
ADDRESS (City, State, and ZIP Code) Department of Bioengineering 220 S. 33rd Street Philadelphia, PA 19104-6392		8b OFFICE SYMBOL (If applicable) NA	
8a NAME OF FUNDING / SPONSORING ORGANIZATION Office of Naval Research		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-78-C-0392	
8c ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington VA 22217-5000		10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO 61153N PROJECT NO RR04108 TASK NO 4414371 WORK UNIT ACCESSION NO	
11 TITLE (Include Security Classification) (U) Microwave Dispersion and Absorption in Tissues; Molecular Mechanisms			
12 PERSONAL AUTHOR(S) Kenneth R. Foster			
13a TYPE OF REPORT Final	13b TIME COVERED FROM 1-1-78 TO 2-28-86	14 DATE OF REPORT (Year, Month, Day) 10 Dec 87	15 PAGE COUNT 12
16 SUPPLEMENTARY NOTATION			
17 COSATI CODES FIELD GROUP SUB-GROUP		18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Dielectric Phenomena, Microwaves, Interfacial Water, Tissues	
19 ABSTRACT (Continue on reverse if necessary and identify by block number) We measured the dielectric properties of materials (tissues, aqueous protein solutions, microemulsions, macroscopic suspensions) from 0.1-18 GHz. These properties are determined over this frequency range by the dielectric properties of water and by ionic effects. Analysis of the data shows that the dielectric properties of the suspending water differ from those of the pure liquid, presumably due to interfacial effects. Similar effects are seen in diverse transport properties and even in nonaqueous systems. The results suggest that water within a couple of monolayers from surfaces have motional correlation times that are tenfold or so longer than those of the bulk liquid. We suggest that this motional restriction is a physical effect due to the presence of relatively immobile surfaces, rather than from chemically-specific binding. This study has led to an improved understanding of the mechanisms of absorption of microwave energy in tissues, and shown the usefulness of comparative studies of transport processes in complex suspensions.			
20 ABSTRACT SECURITY CLASSIFICATION (U)		21 ABSTRACT SECURITY CLASSIFICATION (U)	
22a NAME OF RESPONDER Dr. J.A. Majde		22b TELEPHONE (Include Area Code) 202/696-4055	

## Introduction

This project studied the electrical properties of tissues and other biological materials at UHF-microwave frequencies. On a macroscopic level these properties determine (through the electromagnetic field equations) how an incident electromagnetic field will be diffracted and absorbed by tissue. On a microscopic level, they reflect the molecular processes that are responsible for the absorption of energy. Thus, in two quite different senses they provide direct information about the physical interaction of electromagnetic energy with biological systems.

As an additional benefit, these properties offer direct information about the physical properties of water in biological systems, a matter that has long been a matter of great controversy.

## Goals

The specific goals of this project were to:

- \* Develop instrumentation and methods for the measurement of bulk electrical (dielectric) properties of biological and nonbiological materials from 0.1-18 GHz, using the microwave network analyzer;
- \* Study the dielectric properties of materials over this frequency range. The materials will include tissues, protein solutions and other biological materials, polymer solutions, "phantom" tissue materials, and other suspensions.
- \* Interpret these results using theory of heterogeneous dielectrics, to relate the dielectric properties of these materials to their structure and composition. Of particular interest are the dielectric properties of water in

these materials, as they are modified by interfacial effects.

- \* Study the physical properties of water in biological systems.
- \* Build up a data base of bulk electrical properties of tissues at UHF-microwave frequencies for future application.

### Results

This project has been extremely successful, and has led to many papers and conference publications. These publications, listed below, describe the results in great detail. To summarize:

- \* We developed instrumentation and methods for the precise measurement of electrical properties of materials with such diverse physical properties as soft tissues, bone, as well as solutions and gels, over the frequency range 0.1-18 GHz.

- \* We analyzed the bulk electrical properties of these materials using conventional dielectric theories based on mixture theory, viz. the Maxwell and Hanai mixture equations. The bulk electrical properties of tissues at 0.1-18 GHz are determined principally by the water content of the tissue. A detailed analysis shows that the dielectric properties of this water are similar to those of the bulk liquid; however some changes are observed: there is some broadening of the absorption peak (relative to that of the pure liquid) and a slight increase in the mean of the dielectric relaxation time. These changes can be interpreted as arising from interfacial effects, in which the water within one or two monolayers of surfaces within the sample exhibit rotational relaxation times that are longer than in the bulk liquid by a factor of ten or so.



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\* We studied and compared the dielectric properties of various suspensions and solutions: microemulsions, protein solutions, various polymer solutions. In all cases, the dielectric properties from 0.1-18 GHz were chiefly determined by the water content, with quite similar changes attributed to interfacial water.

\* We extended these studies to include a range of other transport properties in these same materials. The transport properties we measured were water self-diffusion (by NMR techniques), thermal conductivity (by a specially constructed apparatus), and electrical conductivity. All of these properties are subject to the same mixture theory, yet they reflect quite different combinations of rotational and translational correlation times at the molecular level. Thus, a comparison of these properties allows some separation of kinetic from geometrical variables in interpreting the data.

\* We compared these different transport properties using the simple Maxwell mixture theory. We found that all of these properties deviated from predictions of the Maxwell theory, but can be interpreted by the assumption that the water within a monolayer or so of surfaces is hindered in its mobility (as reflected in its various correlation times) by a factor of ten or so. The fact that extent of this reduction in mobility does not appear to depend on the nature of the surface (and was even observed in suspensions with solvents!) suggests that this is a result of a physical effect rather than a chemical affinity between the interfacial water and the solvent (the so-called "bound water" effect).

The "bottom line" of these studies is that water in tissues and other biological materials shows pronounced interfacial effects due to presence of surfaces in contact with the water, but the extent of these effects does not seem to depend strongly on the nature of the surfaces themselves. Similar differences are found in a wide variety of nonbiological (and even nonaqueous suspensions as well. These effects are similar to changes in transport properties that have been reported by many other investigators and attributed to "bound water". However, a more careful analysis, based on the large set of diverse results obtained in this study, suggests that the underlying mechanism might be a physical hindering of the solvent due to the presence of relatively immobile surfaces, not a chemical binding between water and solid.

The mechanisms for absorption of microwave energy in tissues thus are similar to those in other high water content materials: dipolar loss in the water and ionic conduction by dissolved ions. This work has shown the usefulness of comparative studies of different transport phenomena in the study of effects of interfaces on solvent properties.

#### Graduate Students Supported

Several graduate students have been wholly or partially supported by this project:

Erik Cheever

Benjamin R. Epstein

Amanda Hill

Jeffrey Kosterich

Jonathan B. Leonard

Jonathan Schepps

Susan Rae Smith

I note that Drs. Epstein and Schepps are working with industry as microwave engineers directly or indirectly on important aspects of the Navy AEGIS project.

#### Other Pertinent Information

K. R. Foster was recently elected Fellow of the IEEE for "contributions to determining the mechanisms of interactions between electromagnetic fields and biological systems". Most of the work leading to this award was supported by this Contract.

Papers and Presentations of Work Supported Entirely or In Part by this Contract:

SEMINARS/LECTURES/PRESENTATIONS

The state of water in tissue as determined by microwave dielectric spectroscopy. Baylor University, Department of Physiology, September 1980.

Dielectric properties of tumor and normal tissues. University of Ottawa, Department of Electrical Engineering, July 1981.

Dielectric properties of tissues and heterogeneous suspensions. Talk presented to the Bureau of Radiological Health, Food and Drug Administration, Rockville, MD, December 1981.

On the possible hazards of VLF radiation. Talk presented to a Workshop on VLF Radiation Hazards, Naval Medical Research and Development Command, Bethesda, MD, December 1981.

Dielectric properties of dispersed systems. Rice University, Department of Physics, May 1982.

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